

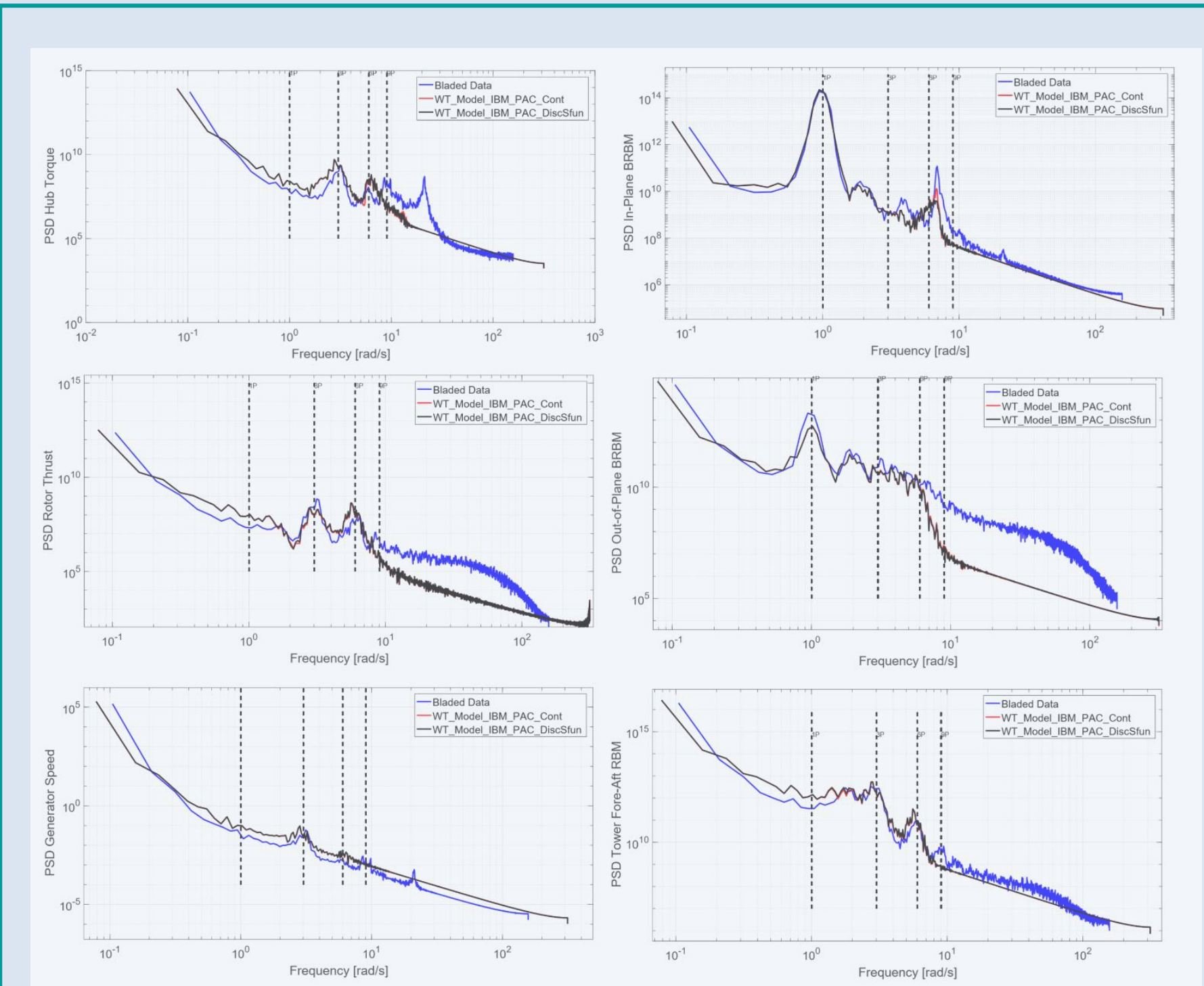
Wind Farm Control at the University of Strathclyde, Past, Present and Future

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Wind Farm Control Simulation Tool Modelling

The University of Strathclyde has developed a Simulink based wind farm simulation model known as **StrathFarm**, designed to be run on a standard modern PC in **real-time or better** (depending on the size of the wind farm simulated). The tool is intended to be **highly flexible** and so contains a wind farm model generator that allows fully flexible model creation (multiple turbine types; wind field of given mean wind speed, turbulence intensity, wind direction, surface roughness etc; any wind farm layout).

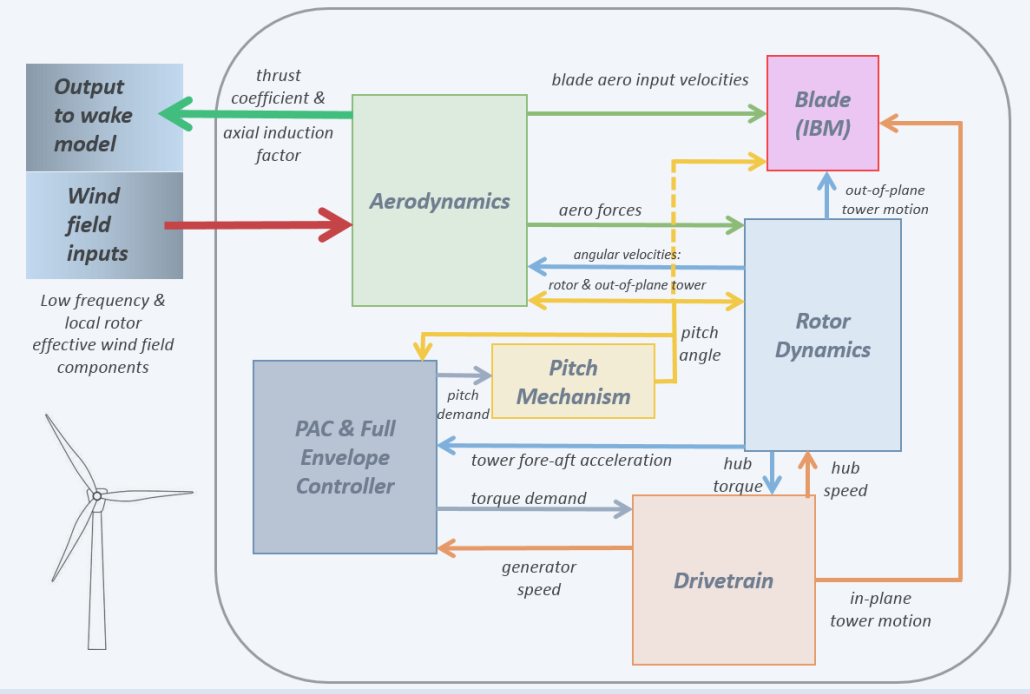
- **Wind Farm Wind Field: Correlated wind farm wind field model** that generates longitudinal and lateral turbulence time series with the required characteristics. The turbulent wind field model is based on the algorithm of Veers, with Dryden gusts. The wind-field time series is generated off-line and is used on-line within a wake deficit calculation to output an effective wind speed for each turbine at each time step. The **wake model** used can be either a kinematic engineering model based on Frandsen or a more complex version based on WFSim.
- **Local Wind Field:** Local wind field model for each turbine. Stochastic and deterministic (**wind shear and tower shadow**) effects modelled which, in the region of validity of separability, induce the correct in-plane moments on the turbine. The time series of the high frequency components of the wind speed is used with the lower frequency component of the wind from the wind farm wind field.
- **Wind Turbine Model:** Supergen variable speed pitch regulated exemplar turbine (5MW, other sizes to be added). Model can include **individual blade model**, which produces blade root bending moments. **Dynamic inflow** (induction lag) is included in the aerodynamics.
 - Comparison of Dynamics: The dynamics of the turbine models are compared to outputs from DNV GL Bladed. Comparisons are shown on the right of the spectra for hub torque, rotor thrust, in-plane blade bending moment, out of plan bending moment, generator speed and tower fore-aft bending moment. There is a good match at the common structural frequencies of 1P, 3P, and 6P.
- **Wind Turbine Control:** Wind turbine model implemented with **Power Adjusting Controller (PAC)**. This allows a dynamic adjustment in power set-point (within limits) without knowledge of the design of the full envelope controller. The output flags and **estimate of wind speed** from the PACs are input to the wind farm controller.
- **Wind Farm Control:** Any wind farm controller can be programmed by the user in C++ to interface with StrathFarm through standardised linking functions. The wind farm controller provides inputs to the PAC to deliver the desired control outputs.



Comparison of spectra from StrathFarm turbines and DNV GL Bladed

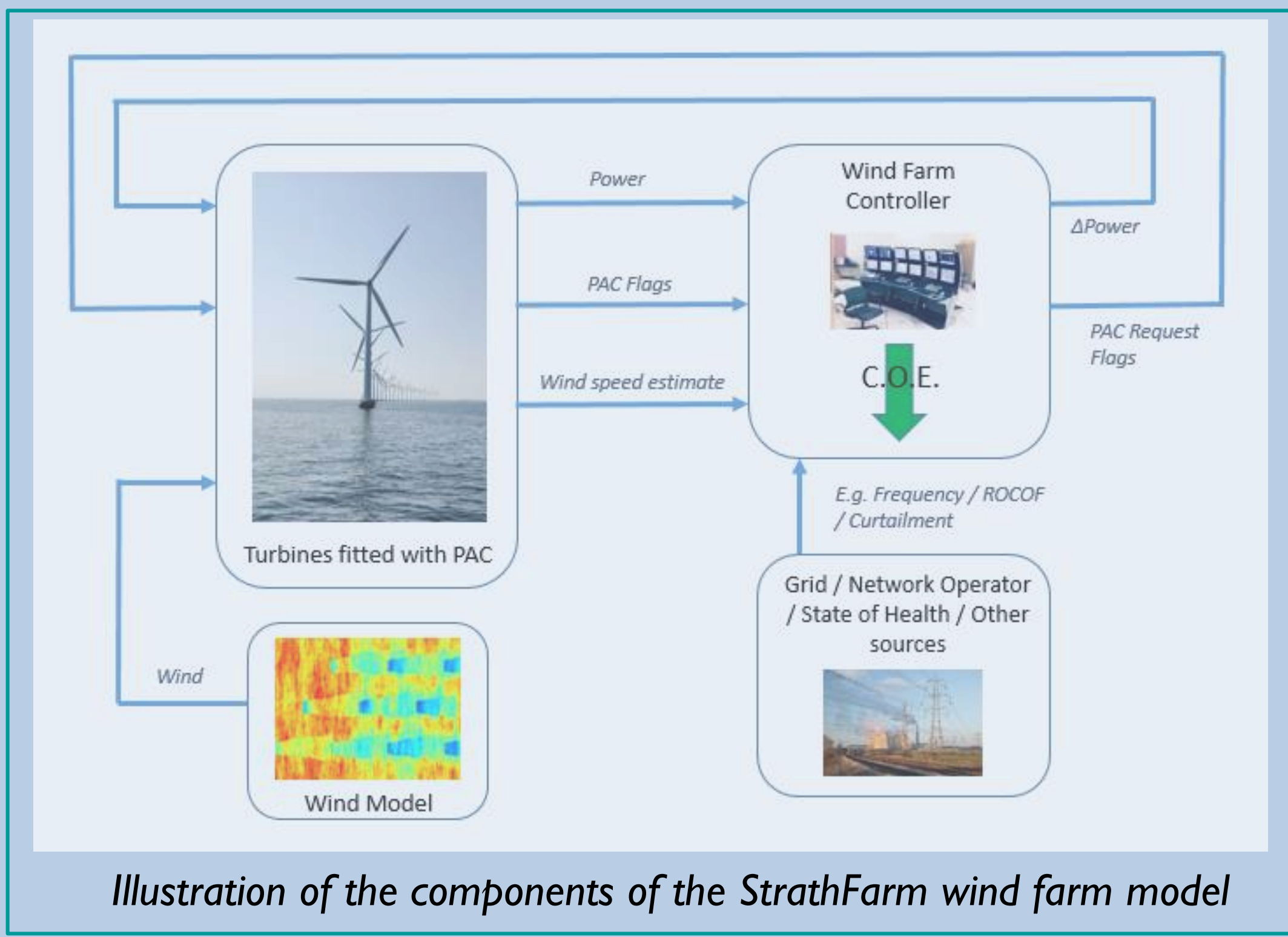
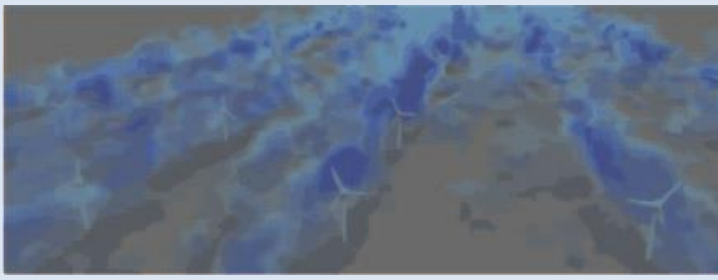
Wind Turbine Model – StrathTurb

- **Supergen variable speed pitch regulated** exemplar turbine.
- 5MW, other sizes to be added (10MW, 1.5MW, possibly 7MW).
- Uses lumped parameter models for representing the drive train and the rotor.
- Reformulated BEM based aerodynamic coefficient models to determine the thrust and torque at the rotor including dynamic induction lag.
- **Valid in-plane moments produced. Loads compare well to DNV-GL Bladed.**
- Model can include individual blade model [6] which produces blade root bending moments.
- Continuous and Discrete forms available.
- Standalone StrathTurb model available, including documentation on theory.



Wind Field & Wakes

- Correlated wind farm wind field
- Rotor effective wind field components
- Wake model can be either a kinematic engineering model based on Frandsen or a more complex model based on Delft's WFSim



Network Inputs

- Current work is looking to expand the capabilities of StrathFarm
- Particularly of interest is integrating a model of the electrical systems of the farm
- Challenges include the difference in time-step size for simulation calculations



Wind Farm Control

StrathFarm can be set up to use any set of wind farm and wind turbine controllers, however, the default is to use the hierarchical method shown on the right.

Wind Farm Power Controller

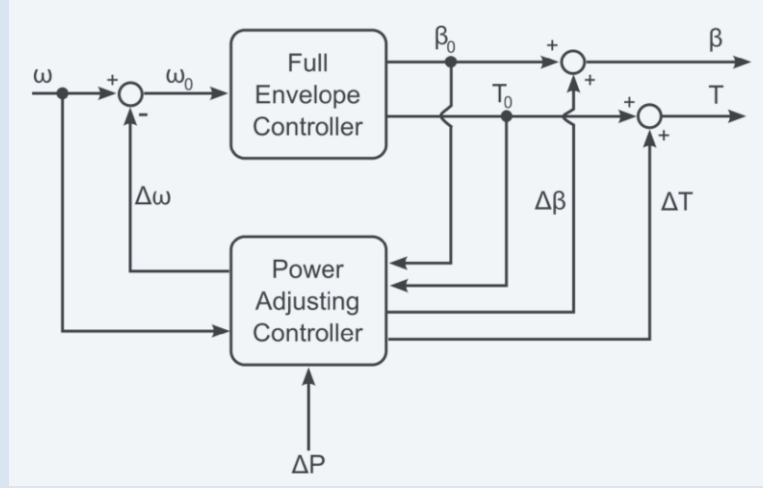
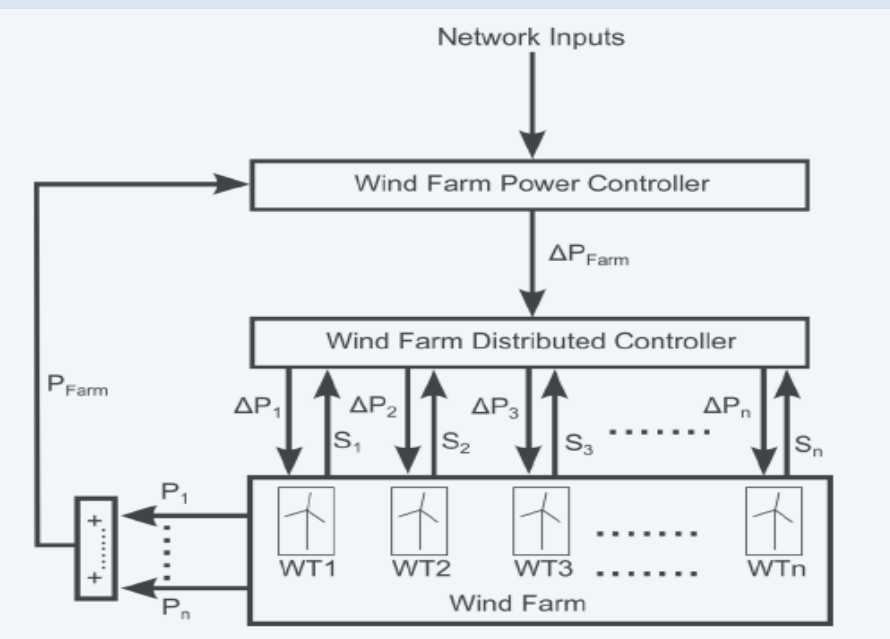
A wind farm power controller receives inputs from outside of the wind farm and uses these, along with the measured farm power to calculate the desired change in farm power ΔP_{Farm} .

Wind Farm Distributed Controller

The distributed controller receives the desired change in wind farm power output and signals from the PAC (see below), which it uses to distribute the turbine changes in power in order to achieve the desired change in power for the farm whilst also achieving another goal such as minimising the farm fatigue loads.

Power Adjusting Controller (PAC)

The PAC is an augmentation to a wind turbine's full envelope controller that allows the power output of the turbine to be varied by a set change in power. As well as adjusting the power the PAC provides information regarding the operational status of the wind turbine in the form of flags sent back to the distributed controller. It also supplies an estimate of the wind speed including induction lag effects.

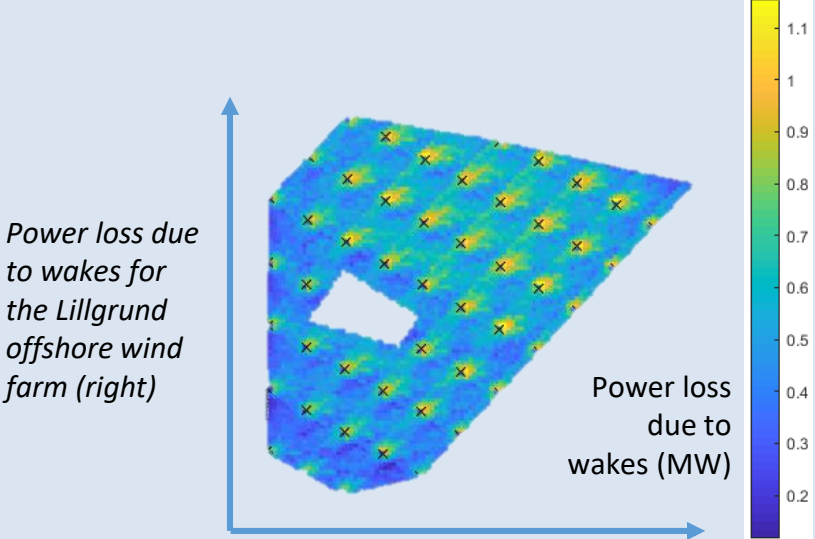


Wind Farm Control Example Applications

Wind Farm Optimisation

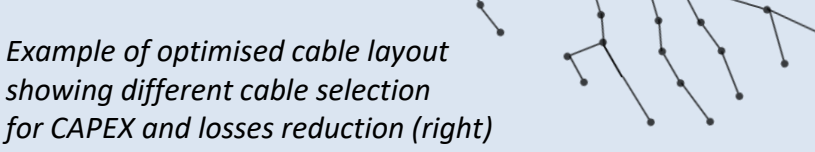
Turbine Placement Optimisation

- Minimising power losses due to wake interaction
- Turbines spacing and distribution increased to minimise interference
- Maximises revenue



Array Cable Layout Optimisation

- Minimising CAPEX and electrical losses through optimisation of the cable layout and cable size selection
- Optimisation is based on overall cable length, electrical losses, additional costs for branching nodes and many other parameters
- Feedback to the turbine placement model can be provided to iterate to a holistically optimised solution



Distributed Wind Farm Control to Minimise Loads

Distributed Control

Whilst setting the correct power output for a wind farm is commonly studied for engaging in strategies such as droop control or active curtailment, a further important consideration is the loads on the turbines. Different turbines in a wind farm experience different wind conditions, hence, how the required change in power is distributed through the wind farm can be optimised to minimise the fatigue loads.

Methodology

The contours of bending moment for the tower fore-aft and the blade out-of-plane against curtailment level and wind speed are shown in the upper right figure. By taking a slice of the surface an initial reduction in power can be calculated. The initial change in power is then adjusted to meet the required farm change in power. The change at each turbine is proportional to the square of the wind speed by an additional change in power such that, for N available turbines, so,

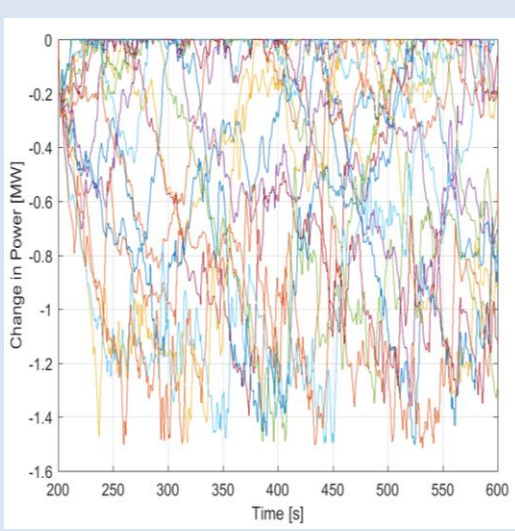
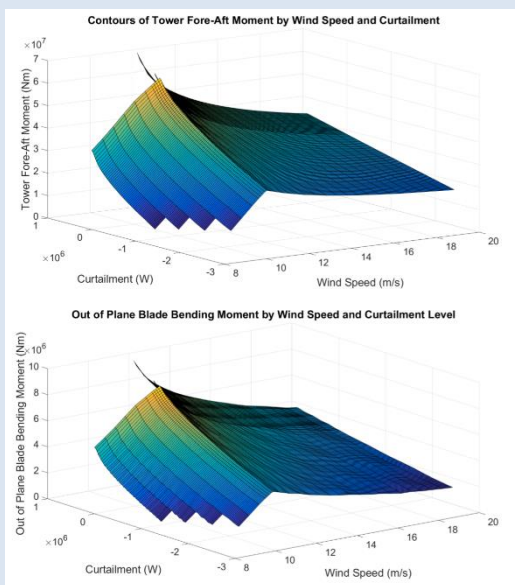
$$\Delta P_{Farm} = \sum_{n=1}^N \Delta P_n = \sum_{n=1}^N \Delta P_n$$
$$\Delta P_n = \Delta P_{nBase} + \frac{\Delta P_{Farm} - \sum_{n=1}^N \Delta P_{nBase}}{\sum_{n=1}^N v_n^2} v_n^2$$

This methodology allocates reductions in power to the turbines most likely to benefit from the reduction.

Impact on Loads

The impact of the outlined methodology on the loads for a "delta" farm control of reducing farm power by 10% of the normal operating value for a wind farm of 16.5MW wind turbines. Two controllers were used for comparison, an Even Distributed Controller (EDC) that distributed the changes in power equally between available wind turbines and the Intelligently Distributed Controller (IDC) that uses the methodology explained above. The IDC produces a greater reduction in the loads for 3 of the 4 wind speeds simulated. The improvement in load reduction from IDC compared to EDC can be as much as 13%, to give a total of over 20%. Future work will extend these results across a wider range of simulations and apply the IDC to the case of curtailing a wind farm.

Mean Wind Speed [m/s]	9			12			15			18		
Direction [deg]	0	22.5	45	0	22.5	45	0	22.5	45	0	22.5	45
IDC Change in Tower DELs [%]	-7.9	-18.8	-14.5	-8.3	-14.9	-13.3	-22.4	-23.1	-22.2	-7.0	-7.6	-5.5
EDC Change in Tower DELs [%]	-1.5	-10.7	-7.7	-14.0	-16.8	-16.4	-10.1	-9.8	-10.3	-4.3	-4.4	-2.2
IDC Change in Blade DELs [%]	-14.4	-20.4	-19.1	-1.7	-9.0	-8.4	-23.4	-23.0	-23.0	-6.8	-7.2	-7.0
EDC Change in Blade DELs [%]	-6.1	-3.7	-6.2	-9.0	-11.1	-12.8	-7.1	-6.8	-7.3	-3.5	-4.0	-3.6



Integrating Energy Storage Systems

De-rating Cables

Further reductions in CAPEX may be found in utilising energy storage systems (ESS) to reduce the required rating of cables.

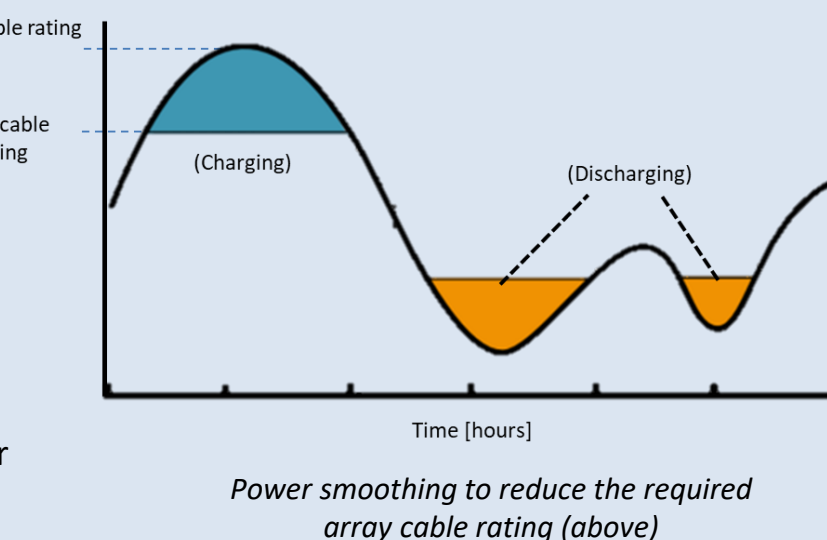
Through controlled charging-discharging, ESS's can reduce the peak power - and current - seen by a cable section allowing for smaller, cheaper, 'under-rated' cables to be used.

On a case study of the Lillgrund offshore wind farm it was found that the size of ESS required to allow for operation in an under-rated network was prohibitively large and not currently cost effective.

Other services...

Distributed ESS within the windfarm may also be able to provide benefits that lead to OPEX reductions. Control of the ESS may be developed to allow for more dispatchable and controllable windfarm power output similar to conventional generation - while avoiding accelerating and decelerating turbines and therefore reducing fatigue loading and failure rate.

- Ancillary services can provide further revenue streams for stacking benefits:
- Enhanced frequency response
 - Black start
 - Power system stability
 - Managing imbalance risk
 - Capacity market



Operating as a Virtual Power Park

Future Grid Services

Wind farms of the future need to be able to provide significantly more by way of ancillary services than current wind farms provide. It is possible, using WFC, to provide the grid with an exact power output, so long as that output does not exceed the energy in the wind for a significant length of time. As such, work focussing on the best way to integrate flexible wind farm level control with the demands of future, low inertia grid systems are an area of active ongoing research. Such grid integration is key to successfully meeting the ambitious climate change targets leading to 2050.